Modeling of Corona Discharge And Overvoltage Propagation Along Transmission Lines

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Abstract

A mathematical model is incorporated into the Alternative Transients Program version of the Electromagnetic transients program (ATP/EMTP), using the MODELS interface introducing the algebraic, differential and Boolean equations, to be solved by the Trapezoidal method. The ATP-EMTP part sets out the additional network elements representing the corona model and discusses the basic aspects of modeling. It simulates transmission lines with the corona effect and computes the attenuation and distortion caused by surge propagation along transmission lines due to corona phenomena with the user-defined multi-branch circuit type94 in ATP. The results of the proposed model are compared with experimental investigations in the literature.

Introduction

Lightning protection and insulation coordination of transmission lines and substations require an accurate knowledge of the magnitudes and waveforms of lightning overvoltage.

High voltages applied to power transmission lines may cause strong electric fields in a small region near the surface of conductors. When the electric field intensity exceeds a critical value, corona discharges will occur in the area surrounding the conductor[1],[2]. They cause radio interference (RI), audible noise (AN), and corona loss (CL) [3]. This phenomenon is related to the electromagnetic environmental problem in the vicinity of transmission lines.

The corona effect has a beneficial effect in the sense that it reduces transient overvoltages which propagate on overhead lines.

The distortion phenomenon is due to the dissipation of energy by injection of space charges around the conductors; it takes place as soon as the instantaneous voltage exceeds the threshold of corona inception voltage [4]–[8].

In this study we chose the Alternative Transients Program version of the Electromagnetic transients program (ATP/EMTP) because it uses the trapezoidal rule of integration. The implementation of the corona model consists of two sections: the MODELS section and its network (ATP-EMTP) section, when we can introduce and solve in the MODELS section: algebraic, differential and Boolean equations. In the ATPDraw part we have the additional network elements as the applied source.

In order to solve the nonlinearity of corona discharge, a number of investigations have turned to circuit representations of the corona discharge, which are considered by introducing nonlinear branches of a diode and capacitance [5]–[8]; other works feature a diode, resistance and capacitance [9]–[11].

Some authors used experimental Q-V data to evaluate the shunt parameters of the equivalent circuit [12]–[16].

The numerical model is adopted in the present paper to evaluate the charge-voltage characteristics and the relationship between the corona inception voltage gradient, and to predict the corona power losses.

The main sources of attenuation are resistive losses in the conductors and ground, losses caused by the occurrence of corona on the conductors and insulator leakage losses. It is important to take into account all these losses in order to determine in a realistic way the overvoltage levels to which power system equipment is exposed.

Corona is a very nonlinear phenomenon and, consequently modeling corona for the calculation of attenuation and distortion is very complex. The literature contains a few experiments [17] and nonlinear modeling [16], [18] including extensive computation in studies of this phenomenon of attenuation and deformation of lightning impulse corona along transmission lines, using analogical models of corona such as: [7], [8], [10], [19]–[21]. This model of corona discharge has been applied to analysis of transient voltages on an overhead transmission line caused by direct lightning strikes to an upper phase conductor.

The objective here is to see if corona can reduce direct-strike overvoltage to below the insulation level of the line.

In order to check the validity of the proposed model, calculated and measured results are compared.

Corona Inception Voltage and gradient

The corona starts when a conductor is subjected to an increasing voltage until the corona inception field strength E_0 (kV/cm) is achieved; it can be calculated by empirical formulas [4], [16], [19].

The corona inception voltage is calculated by the modified Peek formula, given for both conductor configurations

$$V_0 = 31\left(1+\frac{0.308}{\sqrt{r_0}}\right)r_0 \ln\frac{r_b}{r_0}\ [kV] \qquad (1)$$

For a configuration above the ground, the inception corona voltage became[22]:

$$V_0 = \frac{Q_0}{2\pi\varepsilon_0}\ln\left(\frac{2h-r_0}{r_0}\right) \qquad (2)$$

The inception corona voltage as a function of the critical electric field is [22]:

$$V_0 = E_0 r_0\left(\frac{2h-r_0}{2h}\right)\ln\left(\frac{2h-r_0}{2h}\right) \qquad (3)$$

E_0 is the critical electric field on the conductor surface in kV/Cm, when the corona will occur [3], [23]:

$$E_0 = E_a m\delta(1+K_0(\delta r_0)^{-0.5}) \qquad (4)$$

$$\delta = \frac{P_r(T_0+273)}{P_0(T+273)} \qquad (5)$$

Where $E_a = 29.8\ \text{kv/cm}$
h is the higher conductor in m
Q_0 is the geometric charge of conductor.
m is the roughness factor (surface state of conductor) [23] $K_0 = 0.301$
δ is air relative density.
P_r is the atmospheric pressure in kPa, $P_0 = 101\ kPa$ is the environment pressure.
T is the atmospheric temperature in °C, and T_0 is the environment temperature.
r_0 and r_0 are inner and outer radius of the coaxial cylindrical electrode respectively.
V_0 is the corona inception voltage in kV
In this paper we used the Waters empirical formula, [16], [24], to evaluate the minimum critical field E_0, in kV/cm.

$$\mathrm{E_0} = 23.8\mathrm{m}\left[1+\frac{0{,}67}{\mathrm{r_0^{0.4}}}\right][\mathrm{kV/m}] \qquad (6)$$

The effect of air density on the critical field value can be taken into account using:

$$\mathrm{E_0}(\delta) = \mathrm{E_0}\cdot\delta^{\mathrm{b}} \qquad (7)$$

Corona Model

When lightning strikes a transmission line and the amplitude of the produced overvoltage is larger than a certain threshold value (inception voltage), free charges will occur on the conductor surface. These charges form what is called discharge phenomenon or corona.

Corona effects can be modeled in terms of 'corona capacitance' [16]; this nonlinear capacitance is used to compute surge voltages to determine distortion and attenuation phenomena.

Some authors such as [25] Sekar 1982 and [26] Afghani and Harrington 1983 described a numerical model for a cylindrical geometry, based on a methodology of multiple discrete charge shells. The model of Sekar was only used for repetitive voltage pulses, but the model proposed by Afghani was used for switching overvoltages and suffered numerical instability. This model is used to calculate the corona attenuation of switching surges particularly for long lines, but it suffered numerical instability.

In [4], [27] Semlyen and Wei-Gang 1986 proposed a macroscopic model inter-relating space charges, electric field and voltage in cylindrical corona geometry, when the space surrounding the conductor is divided into three separate regions: two non-ionized regions, an external region to a fictitious cylinder of radius R, and a region between the cylinder of radius R and a cylinder of radius X. The third, ionized, region is between the cylinder of radius X and the conductor of radius R_0.

Gallagher et al. in 2004 [18], presented a mathematical model of corona phenomenon for a study of lightning applied to a 110 kV overhead line under the influence of overvoltage surges.

In 2007, Xiao Zhang studied corona characteristics under nonstandard lightning impulses (under damped oscillatory and double exponential impulses) based on experimental investigation, using a corona cage with a coaxial cylindrical electrode system, with two guard rings. He proposed a numerical corona model to calculate the charge-voltage curves under damped oscillatory impulses for positive and negative polarities. The results obtained in experiments are in good agreement with the calculated values.

X. Zhang and his groups in 2015 conducted similar studies in experimental tests and proposed a new corona model which took into account the effect of collision ionization, drift of charged particles, space photoionization, attachment and recombination.

This corona model is based on the following assumptions:

- The corona discharge depends on line geometry, the form of overvoltage applied wave.
- The streamers are propagated with extremely high speeds of 1m/mS or more.
- The length of streamers depends on the wave form, voltage polarities, and values of the superficial electric field and the geometric characteristics of the conductor.
- The space charge is emitted at peak voltage in the form of a hull of unipolar charge, where the field takes as its external limit the value of the streamer propagation field E_C, which is equal to 5 kV/cm for positive polarity and 18 kV/cm for negative polarity.
- The electric field at the corona electrode is restricted to the value E0 of the corona inception field, as determined by the empirical formula of Peek [23].

In this study we make use of the above assumptions to resolve the equations which predict the corona phenomenon in order to create a new model for the computing and modeling of corona characteristics. At each time step, the conductor under corona generates a thin shell of space charges. This shell moves away from the conductor under the influence of the local electric field [24], and this movement was computed iteratively by the Dichotomy numerical method.

During the corona process, the charge q bound on the conductor takes the critical value q_0, after a new shell of charge emerges from the conductor when the instantaneous charge q exceeds this critical value.

This model is incorporated into ATP-EMTP using the MODELS feature of this program. This nonlinear component of capacitance is introduced in the type-94 element of ATP, and is inserted along the transmission line, in order to compute the attenuation and distortion of the lightning-induced surges as they propagate along the line.

Corona characteristics

This model supposes that the corona effect appears due to the emission of a very thin layer of electric charge at voltage peak around overhead transmission line conductors. It is used in order to predict the nonlinear variations of the corona characteristics Q-V curves. We studied it for two configurations: coaxial configuration and conductor placed above ground.

Cylindrical geometry

For this configuration, the critical charge corresponding to the critical corona onset voltage becomes equal to the geometrical charge:

$$q_0 = C_g V \quad (8)$$

And the slope of this curve becomes the geometric capacitance of the conductor.

$$C_g = \frac{2\pi\varepsilon_0}{\ln\left[\frac{r_b}{r_0}\right]} \quad (9)$$

We can determine the amount of space charge for a given voltage, where the total charge increases in

proportion to the increase of voltage from V_0 to V around the conductor is given by [16], [26].

$$\mathrm{Q} = \mathrm{C_g V} + \mathrm{q_{sc}} \quad (10)$$

For a coaxial system having an inner radius r_0 and an outer radius r_b, the Q –V curve is calculated as [16], [26]:

$$Q = 2\pi\varepsilon_0 r_c E_c \quad (11)$$

$$\mathrm{V} = \mathrm{E_0 r_0 ln}\left[\frac{\mathrm{r_c}}{\mathrm{r_0}}\right] + \mathrm{E_c r_c ln}\left[\frac{\mathrm{r_b}}{\mathrm{r_c}}\right] \quad (12)$$

For this geometry, the critical voltage is calculated by the equation (1):
Where r_c is the corona shell radius (in cm)

In absence of the corona (i.e. for $V < V_0$): $r_c = r_0$
To resolve these two equations (11 and 12) we used a numerical method to obtain the radius r_c for any voltage $V > V_0$. In our case we used the Dichotomy method.

To compare the results of our corona model with others adopted by other authors, we used a coaxial system with: $r_0 = 0.475\ cm$ and $r_b = 29.05\ cm$, applying a switching voltage (120/ 2200 µs) to the inner conductor, the variations of the initial position r_c of charge shells and total charge, are shown in figures (1) and (2), respectively. Good agreement can be seen between the simulated results and those obtained experimentally that are available in the literature [28],[6].

When the voltage is below the critical threshold, the space charge is zero, and the total charge takes the value of the geometrical one. After the appearance of corona, the space charge has nonlinear variation and it increases with the increasing applied voltage; the total charge becomes equal to the sum of the geometrical charge and the space charge; after the peak voltage value the total charge decreases and is closed by geometric capacitance. And the slope of these three parts produces the variation of conductor capacitance, as shown in figure 3. When the corona capacitance for this geometry becomes [27]:

$$C_c = C_g \frac{\ln(r_c/r_0)}{\ln(r_b/r_c)} \quad (13)$$

The experimental results were compared with the calculated values [28], [6] and found to be in good agreement.

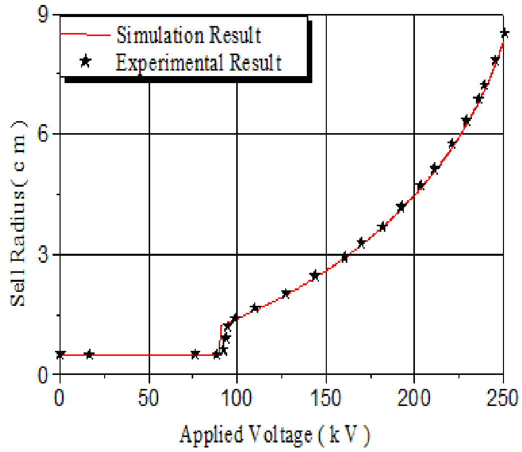

Figure 1: Variation of the initial positions of the hulls compared with experimental results

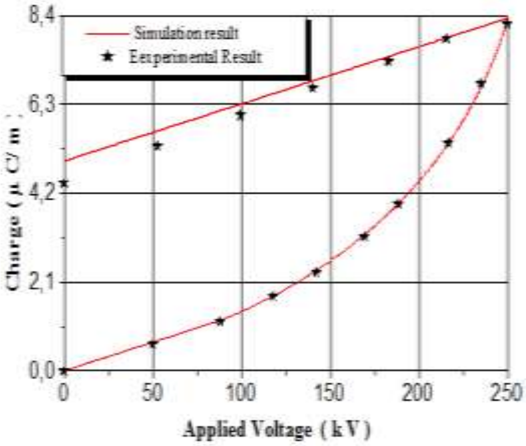

Figure 2: Variation of the total charge of simulation compared with experimental results [28], [6]

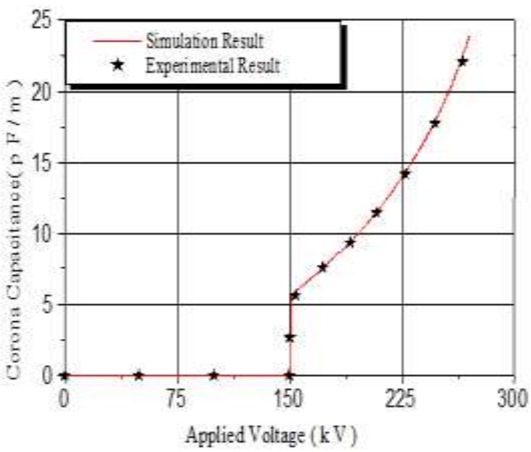

Figure 3: Nonlinear variation of corona capacitance for the coaxial system

Under grounding geometry

The Q-V diagram is calculated by the corona inception voltage and the charge bound on the conductor, [1], [16]

$$q = 2\pi\varepsilon_0 X_c E_c \left[\frac{2h - X_c}{2h}\right] \tag{14}$$

$$V = E_0 r_0 \ln\left[\frac{X_c(2h - r_0)}{r_0(2h - X_c)}\right] + \frac{E_c X_c(2h - X_c)}{2h} \ln\left[\frac{2h - X_c}{X_c}\right] \tag{15}$$

Resolution of the two equations above by one of the iterative methods will give the positions of the corona shells. We used the Dichotomy numerical method for resolution purposes.

The corona capacitance for this configuration becomes [1]:

$$C_c = C_g \frac{\ln\left[\frac{(2h - r_0)X}{(2h - X)r_0}\right]}{\ln\left[\frac{2h - X}{X}\right]} \tag{16}$$

The Q–V diagram can thus be computed as the total charge generated. Calculation of the change in line capacitance becomes easy as it can be obtained from the slope of the Q–V diagram. Computed Q–V diagrams have been found to agree quite accurately with the experimental results available in the literature [29] and are presented in Figures 4 and 5 for conductor radius of 1.32 cm situated at 7.5 m of height.

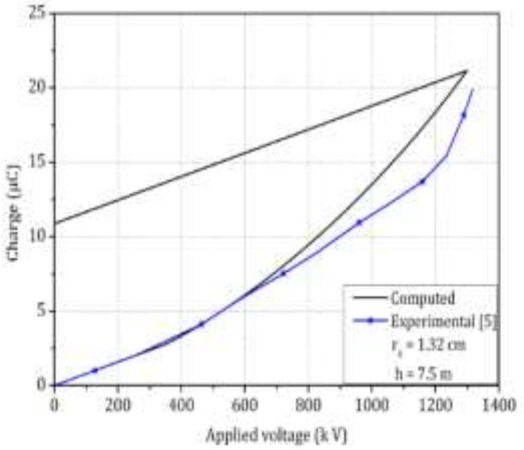

Figure 4: Q–V diagram for a 1300 kV peak, 1.2/50 ms wave.

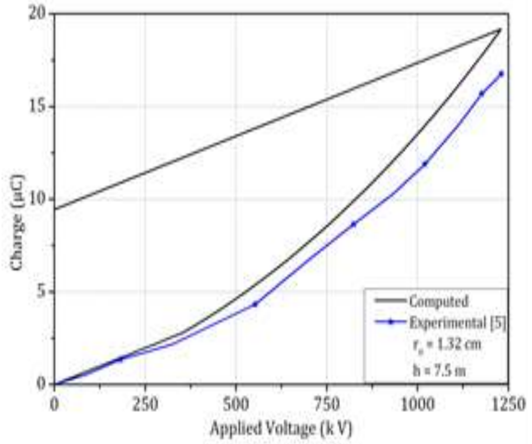

Figure 5: Q–V diagram for a 1230 kV peak, 10/75 ms wave.

Simulation of surge corona on transmission lines

Surge corona should be considered when we study lightning protection schemes and insulation coordination for their effects on the overvoltage lines. Corona attenuation and distortion of overvoltage waves are an important factor in determining the overvoltage level when the impulse corona is modeled as nonlinear capacitance added between the transmission line and ground.

This following section shows the simulation of overvoltage wave propagation in an electrical network by digital computers and provides a description for lightning overvoltage studies.

Transmission line modeling

The overhead transmission line is simulated by J. Marti's multi-conductor model. Input data consists of the conductor's geometric configuration, its diameters and geometry of bundles.

Line parameters are calculated using LINE CONSTANTS routine of the EMTP, and the line Characteristics of J Marti TL are shown in figure 6.

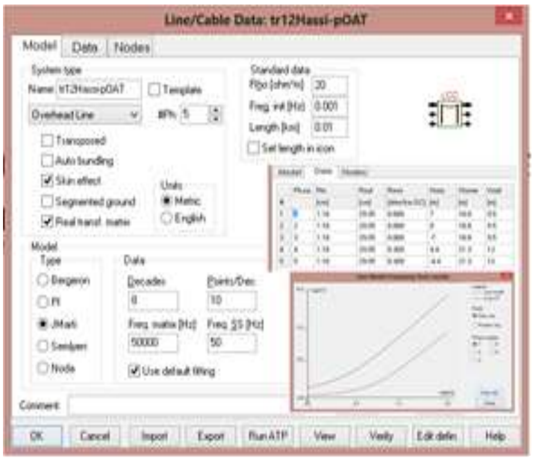

Figure 6: Characteristics of J Marti TL

Corona Modeling for Transmission Line

The following shows implementation of an accurate numerical model representing the nonlinear corona phenomenon in a general purpose electromagnetic transients program (EMTP) using type-94 interface.

Magnitude of 1 800 kV and a (1/5 µs) wave are applied on a transmission line comprised of 135 sections of 5m length, for a conductor radius 1.18 cm located at an altitude of 20 m.

Each section of the line is connected in cascades with the nonlinear element of Norton to represent the corona capacitance (Fig. 7).

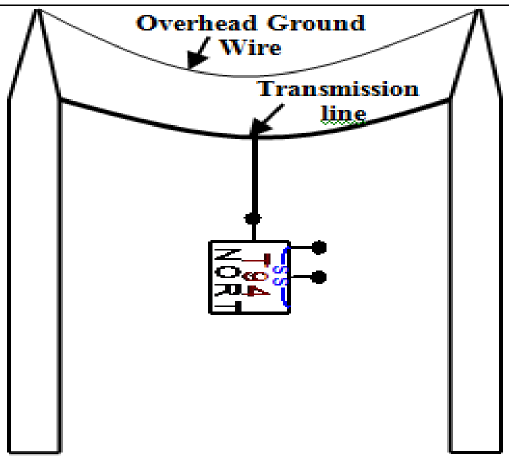

Figure 7: Structure of a section of the single-phase line with element TYPE94 NORTON

Section line length influences the propagation wave. The model response is illustrated in Fig. 8, when we use lengths of 5 m, 10, and 15 m at a distance of 450 m from the feeder. Substantial differences are apparent in the results of this simulation.

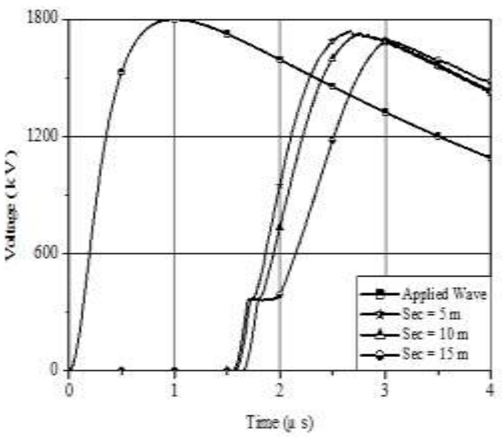

Figure 8: Effect of section length

To confirm the confidence of this corona model, we use a crest voltage value of 1 280 kV. The deformation suffered by a surge due to corona has been found to be satisfactorily reproduced by the corona model and the computed result is presented with the experimental values of Wagner in Figure 9. The wave shapes show the typical distortion of the wave front and reduction in crest values associated with corona losses.

As an observation, attenuation of the peak due to corona effect is greater for surges of shorter tail duration than surges with a longer tail. Computations were carried out to compare the attenuation and distortion occurring due to corona on 1.2/50 and 1/7.5 µs surges of same peak amplitudes. The results show that attenuation of the surge is appreciably higher in the case of 1/7.5 ms surges. The computed results are presented in Figures 10 and 11. These results are also obtained by [16]and in the reference [29].

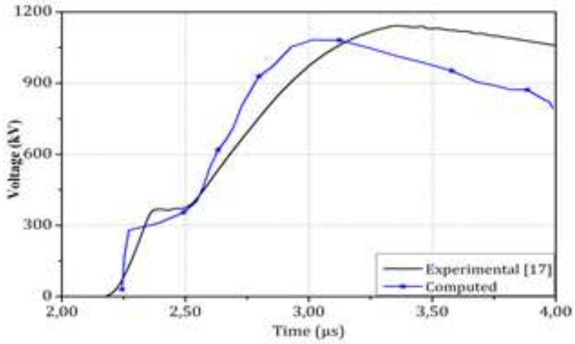

Figure 9: Voltage waveform at 620 m

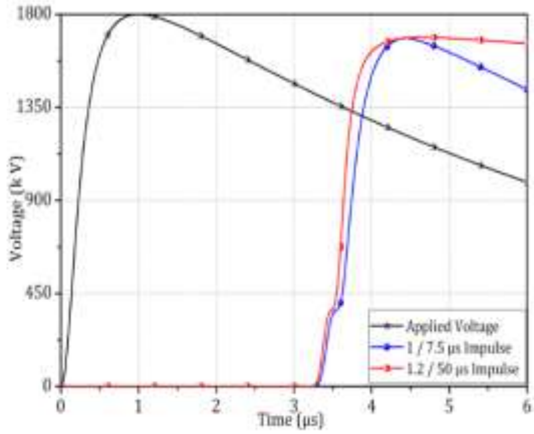

Figure 10: Voltage wave form at 1000m for an input of 1800kV peak

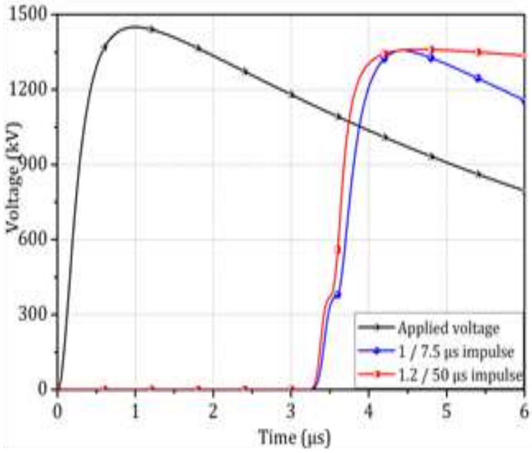

Figure 11: Voltage wave form at 1000m for an input of 1450kV peak

We integrate the corona model in each phase of the three-phase transmission line. The line is of horizontal design as shown in figure 12.

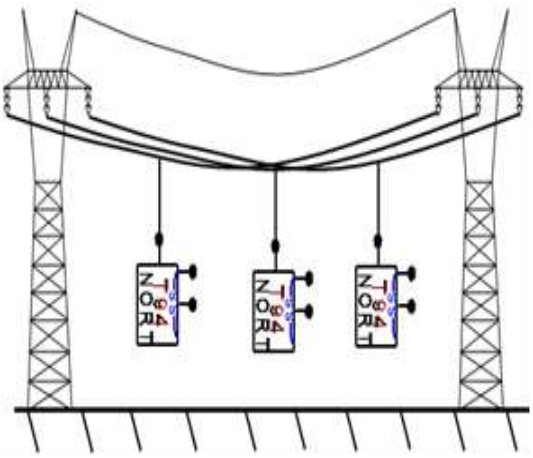

Figure 12: The equivalent circuit of a three-phase transmission line with corona.

This line is divided into 45 sections, each 25 m in length. Figure.13 shows the computed wave shapes including corona. It may be seen that the corona losses produce the greatest attenuation and distortion of the surge voltage.

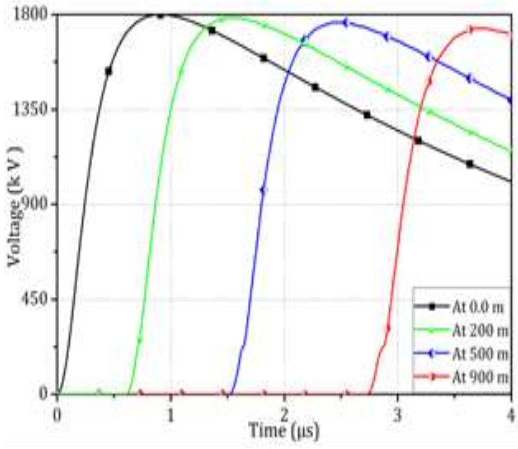

Figure 13: Computed surge voltage with corona losses

In this case, we integrate the corona model in each phase of the three-phase transmission line with two earth wires.

This line is divided into 45 sections, each 25 m in length. The result of this investigation, shown in figure 14, is that for the line with earth wire, the delay of wave is weaker and we also notice an increase in the attenuation of wave compared to the delay and attenuation in the line without earth wire.

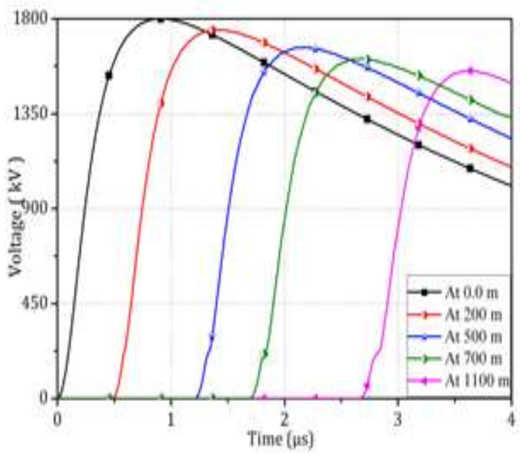

Figure 14: Computed surge voltage with earth wire

Conclusion

A corona model has been developed to simulate lightning transients on transmission lines, predict the charge voltage diagram, and to eliminate magnitude after reaching the transformation substations along overhead transmission lines.

The mathematical corona model developed in this paper was incorporated into a transmission line model. It was developed to illustrate the effects of nonlinear corona phenomena on overvoltage wave propagation in overhead transmission lines and for computing corona power losses.

This model is based on a charge voltage diagram and was developed for it to be applicable to any transmission line geometry, because all model parameters can be determined in advance according to the conditions of the line under consideration.

The attenuation and distortion suffered by the surge as it propagates along the overhead line due to corona phenomena was computed by this mathematical model in EMTP software using the MODELS interface.

The corona is modeled with the use of a dynamic capacitance idea. Corona model blocks are connected to nodes in LCC sections, which contain a nonlinear Norton type-94 component.

Simulations on our ATP-EMTP model, which show good agreement with experimental data, show the importance of including a corona model in lightning studies. It is shown that consideration of corona affects the attenuation and distortion of the return-stroke current.

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